Title

Multi-stage sound planning methodology for urban redevelopment

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Abstract

Due to its local character, there is a tight link between the environmental noise issue and urban planning. Although the need for sound planning has been advocated since decades, limited information can be found on what this now means in practice. In this work, a methodology to internalize sound in the urban planning process is presented, applied to a major redevelopment project of a city ring road. The specific interest in increasing green infrastructure, and at the same time, tackling environmental noise, makes this project timely and challenging. Noise experts took part in an intense co-creation process with the spatial planning teams, where also dwellers were involved. Interactions ranged from conveying general information on environmental noise, providing solutions tailored to the local setting, qualitative expert opinions on initial plans, and assessing the applicability of uncommon noise abatements with numerical tools. The latter is important as the noise reduction potential of such measures could strongly influence the next round of spatial planning. Each planning phase should be optimized to allow maximum freedom in the next iterations. While evaluating various planning scenarios, separate acoustic goals were set for the sound exposure at dwellings, in the public space and along soft connections.

keywords : environmental noise, urban sound, sound planning, road traffic noise

1.Introduction

Although the need for urban sound planning has been advocated since decades (Blucher & Walter, 1956; Purkis, 1964; Brown & Muhar, 2004; Alves et al., 2015; Barrigón Morillas et al., 2018) clear methodologies applicable to large redevelopment projects are missing. City densification, often seen as sustainable city growth (EAA, 2006; Kremer et al., 2019), will make that more sound sources and more people will be closely packed together, further increasing their noise exposure. Consequently, more negative health outcomes (Fritschi et al., 2011; WHO, 2018) and a further decrease in the quality-of-life of citizens (Botteldooren et al., 2011) can be expected. Already now, the environmental noise issue in urban environments is a major threat. Traffic noise is the second most important cause for environmental burden of disease in Western Europe, behind only air pollution by fine particulate matter (Hänninen et al., 2014).

Early viewpoints treated environmental noise analogously to air and water pollution. A major difference, however, is the local character of environmental sound. The related air pressure and particle velocity variations due to sound waves have a rather limited scope and leave no traces in the surroundings. Yet, they do have the ability to strongly and directly impact people at close distance. This local scope also implies that local measures could be effective, leading to a close relationship to (landscape) architecture and urban planning (Blucher & Walter, 1956; Purkis, 1964; Brown & Muhar, 2004). On the other hand, noise abatements are typically only locally effective as well.

Environmental sound (or even noise) in a city is not necessarily unwanted (Schafer, 1994; Brown, 2010; Kang et al., 2016). One can think of the vibrant atmosphere in an outdoor market place or the sound of church bells reverberating over an urban square, adding to the identity of that place (Schafer, 1994). Soundscape approaches linked to urban sound planning and design have been researched before and inspiring examples can be found (see e.g. Lavia et al., 2016; Kropp et al., 2016). Many researchers showed that (absolute) sound pressure levels alone are insufficient for predicting the reactions people have in response to sound. Thus, urban sound planning should surpass the concept of A-weighted sound pressure levels representing a specific “dose”. At the other hand, when dealing with road traffic or industrial sound sources, purely relying on the aforementioned soundscape approach would make no sense either. This means that a location-dependent diversification of the goals and limits is needed. Note that in most countries and cities, such quantitative goals or limits are non-existent and noise policies are strongly complaint driven (for instance based on noise annoyance reactions and sleep disturbance reported by the citizens). The latter cannot be directly translated to the urban sound planning process. An essential but non-trivial task is thus defining and quantifying diverse and evidence-based acoustical goals.

Urban planning, in general, could largely benefit from citizen involvement (e.g. Brody et al., 2003; Boonstraa and Boelens, 2011). Nowadays, such participation can be facilitated by ICT solutions (e.g. Ertio, 2015; Wilson et al., 2019). In redevelopment projects, citizen involvement could be especially interesting, not only because most people that will inhabit the specific area are known, but also since they are well aware of current issues. They are the “local experts”. People experience sound everyday, making this environmental stressor tangible, in contrast to other forms of pollution. Involving locals in urban sound planning could thus be especially interesting (see e.g. Schulte-Fortkamp, 2010; Xiao et al., 2017). Common practice, however, is presenting nearly finalized plans to interested citizens in the end with the option to amend, after which only a small number of corrective but most often less efficient noise abatement measures are possible. A deeper involvement should include citizens or their representatives early in the planning process, making the participatory process co-creative.

In this work, a multi-stage sound planning methodology is described, applied to a multi-billion real-life urban redevelopment project along a major highway/ring road in the city of Antwerp (Belgium). The specific role and tasks of the noise experts are highlighted, as they played an important role throughout this process. The basic idea of considering environmental noise early in the planning process is followed here which is rarely achieved in practice. This enables other types of solutions and avoids ending up with common noise walls only as a corrective measure when plans are (more or less) finalized.

2.Case study and background

The re-development of the Antwerp ring road area is considered, which comes along with the completion of the city ring road (see “missing link” in Fig. 1). The Antwerp region (with approximately 517 000 inhabitants, 2016) is located at the centre of the Trans European Transport network (TEN-T), where three corridors pass through the city, connecting - in a multimodal way - the port of Antwerp with major European cities such as Paris, Brussels and Amsterdam. The Antwerp ring road is a major transport link (> 300 000 vehicles per day, 27 % freight traffic) and is currently facing great mobility challenges and structural congestion.

The ring road cuts the city of Antwerp in two parts. Because of the continued urban expansion over the past decades, the zones bordering the ring road became densely inhabited. The close proximity to the intense arterial road jeopardizes the livability in this region. Main environmental issues are excessive exposure to air pollutants (Van Brusselen et al., 2016) and road traffic noise. In this work, the focus is on the environmental noise problem. Nearly 100 000 inhabitants in the Antwerp agglomeration are exposed to road traffic noise levels at the facade exceeding 65 dBA L_{den} (Flemish Government, 2019), far beyond guidelines set forward by the World Health Organization (WHO, 2018). More than 40 % of the people living in Antwerp declared to be suffering “often to always” from environmental noise (Flemish Government, 2018).

In the current project, green solutions will get a prominent place, since the lack of accessible and qualitative green space was found to be another major problem in this region. There is thus a specific interest in measures that increase green infrastructure, and at the same time, tackle noise (and air pollution) exposure. This makes the project especially challenging and timely. Recent findings showed that sound exposure reductions by natural means are indeed possible (Van Renterghem et al., 2015), including the clear benefits vegetation has for the perception of environmental noise (Van Renterghem, 2019).

The re-development aims at making the area that surrounds the ring road more suitable for dwellings, but also to create new public places with a variety of functions such as recreation and sports, commercial use and mobility hubs. The absence of buildings and dwellings very close to the ring road allows road coverings. Capping the ring road as much as possible was strongly pushed by various citizen action groups and is the preferred solution. However, the specific situation of the highway, with many exits, but also budget constraints, will not allow a full covering. The non-covered parts of the ring road are then expected to dominate the noise exposure in the area since tunneling roads can be a highly efficient noise reducing measure. The design of flanking measures at the uncovered parts of the ring road are thus of main concern in the acoustic design. The possibility to intervene in the landscape in the current project gives ample opportunities to limit environmental noise exposure.

To organize the re-development of this large area, six design teams were assigned a specific zone. Their task was to propose a spatial development plan phased in time, including capping specific segments of the ring road, but also to design the aforementioned flanking measures for the non-covered parts. Various interactions were organized with stakeholders, including the public at large or their representatives, several layers of government, and topical experts on ecology, mobility, air quality and environmental noise. A 9-month period was assigned for the planning that should lead to the identification of a number of initial demonstration projects. These should allow gaining experience with the measures promoted and to step towards the final goal of completing the ring road while improving the livability of the zone.

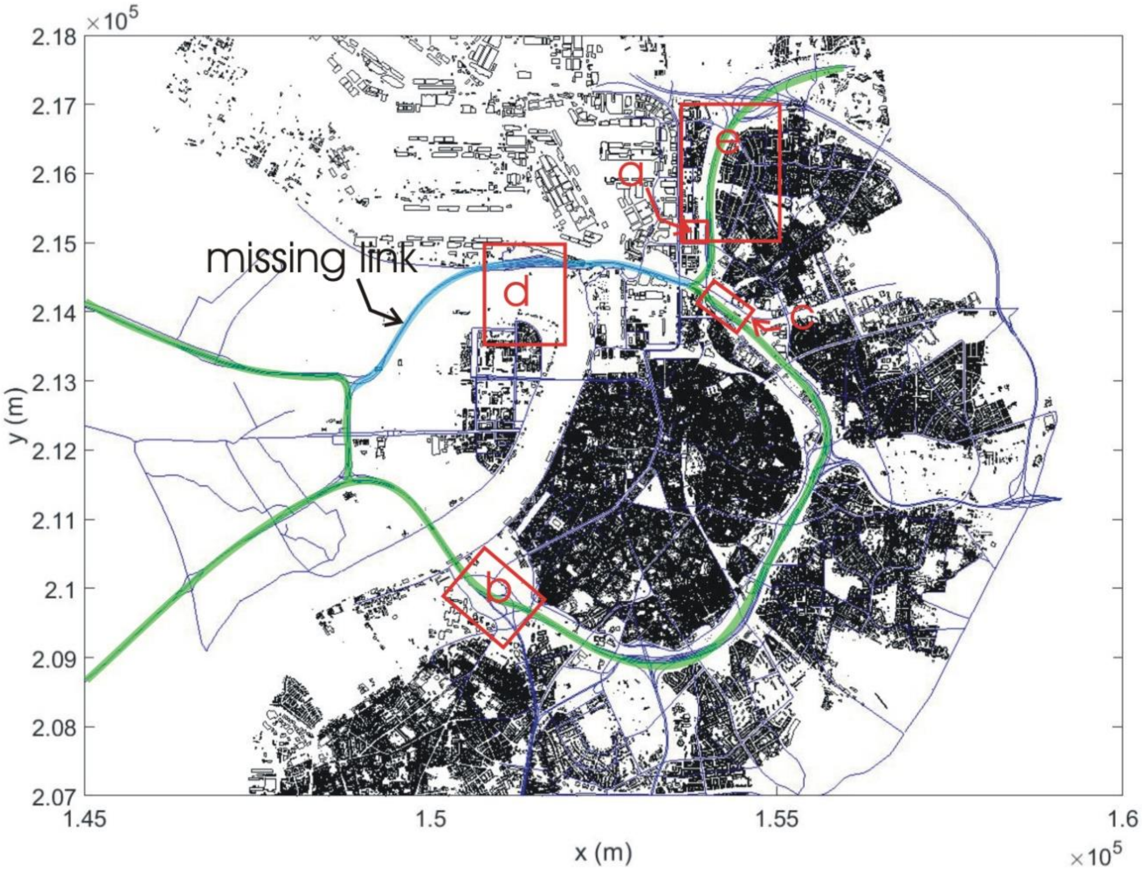

Figure 1. Overview map of the ring zone, indicating the missing link, and the positioning of specific zones used as examples for the sound planning procedure.

3.Multi-stage urban sound planning

3.1.Step 1 : Inform

If urban sound is to take its rightful place in the design phases, all parties involved need to have a minimum knowledge on sound. However, this is most often lacking. So the acoustician(s) should translate general expert knowledge to information that can be locally applied and that is understandable for non-experts.

The effect of noise abatement solutions focusing on sound transmission between source and receiver is often difficult to generalize. For road traffic noise, the efficiency of such measures strongly depends on the very local settings, such as the position of the road relative to its surroundings (whether the road is depressed or on an embankment, the number of lanes, the presence of a central reservation, etc.) and where the zones to be shielded are located (such as visitors in the public space or at specific heights along the facades of dwellings). During iterative planning, it is practically impossible to simulate the noise exposure in the whole area upon each change.

Therefore, in the current project, the noise shielding efficiency of a number of desired measures (more precisely combinations of natural berms and vegetation scenarios) were simulated in standardized cross-sections of the depressed ring road under study (see Fig. 2). Previous research showed that non-steep and acoustically soft berms could be especially interesting to abate road traffic noise (Hutchins et al. 1984; Busch et al., 2003; Van Renterghem and Botteldooren, 2012). Although this information cannot be directly transferred to each future design proposed by the planning teams, it already gives a good indication of what measures could work. Given the complex nature of the sound propagation problem, an advanced full-wave outdoor sound propagation techniques was used for this task (Van Renterghem, 2014). A successful validation of this simulation model with measurements at a specific location along the ring road is reported in detail by Van Renterghem and Botteldooren (2018).

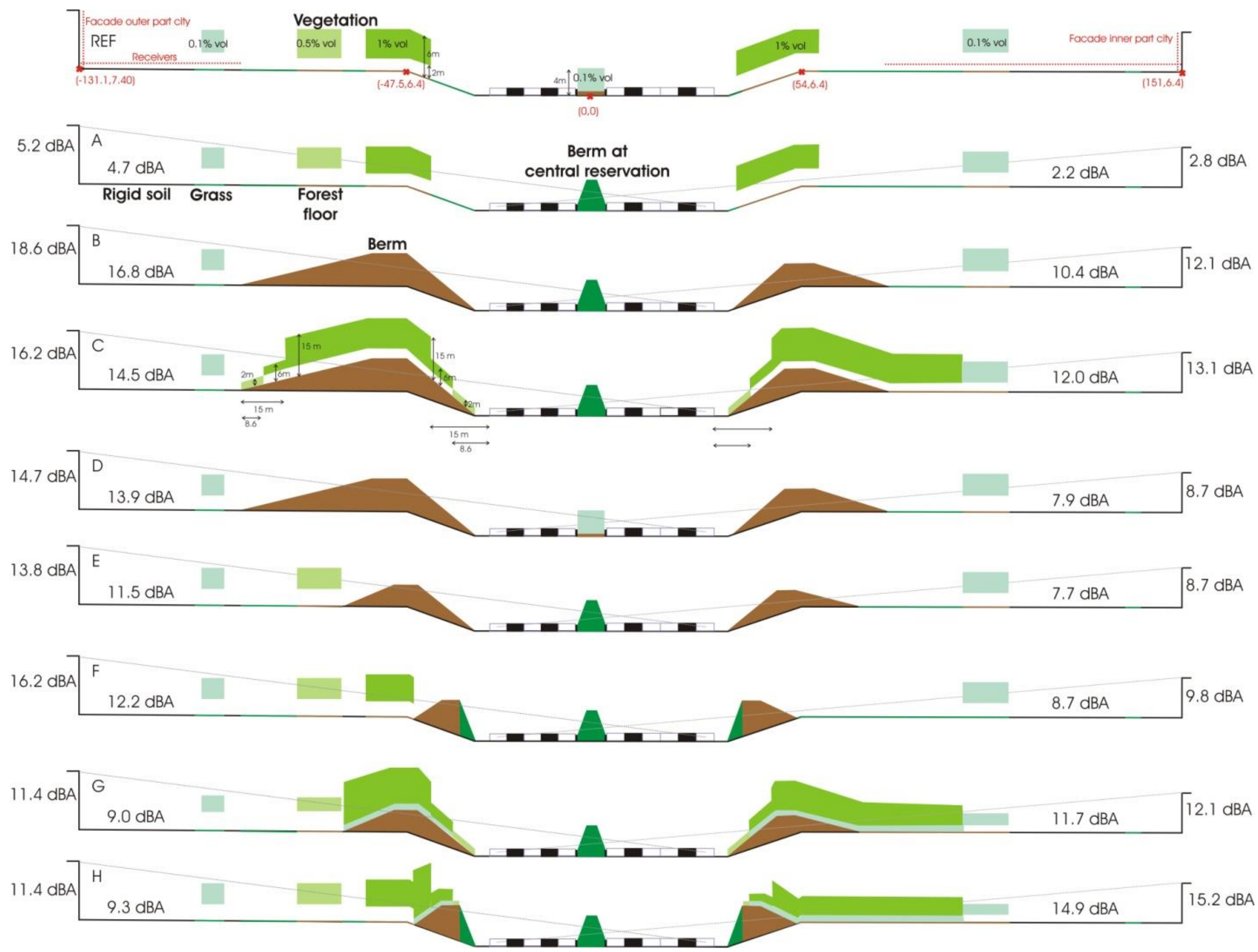

Figure 2. Results of detailed simulations in a typical cross section near the ring road. A combination of berms of various shapes (at the road borders and on the central reservation) and vegetation scenarios (with various densities) were considered (scenarios A-H). Averaged road traffic noise shielding relative to the reference case (REF) is shown, along the building facades and in the public space (at a fixed height of 1.5 m). Atmospheric effects (see e.g. Salomons, 2001; Attenborough et al., 2007) and local traffic were neglected, while the noise abatement solutions are assumed to be of infinite length corresponding to the two-dimensional approach followed here, making them maximum effects.

Such modeling exercises, tailored to the local setting, were assembled in a “catalogue” and made available to the design teams. The editing was performed by the city’s environmental planning department to ensure it is sufficiently understandable for non-experts.

The catalogue has multiple goals:

- Ensuring that livability and environmental aspects get sufficient attention by the planning teams that might otherwise only focus on landscape and visual design. A visually attractive public space, but with excessive noise exposure, might have a limited use in the end.
- Ensuring that up-to-date noise mitigation solutions are considered in line with the city's green vision on the ring zone.
- Providing quantitative data on specific measures allowing a first comparison of various planning choices.
- Shedding some light by topical experts on misconceptions that might be present related to specific measures. Especially for the interaction between sound wave and natural solutions, common engineering type methods used for noise mapping might be inaccurate (Attenborough et al., 2007).
- Allowing to compare the impact of the same measures on different environmental stressors, thus providing a common reference framework. An extract is shown in Fig. 3, where the same measures were roughly categorized based on their noise shielding efficiency, air quality impact and heat stress.

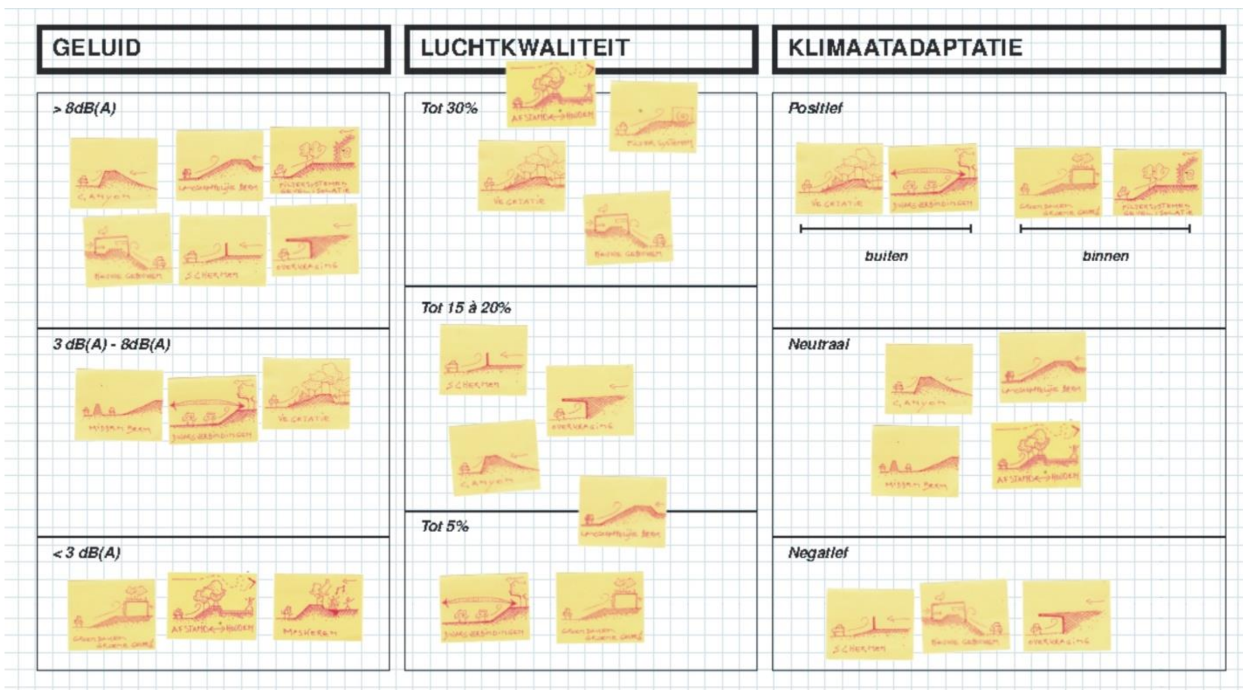

Figure 3. Extract from the livability matrix for environmental noise ("geluid"), air quality ("luchtkwaliteit") and climate adaptation ("klimaatadaptatie"). The rough classification of the effect of the measures is based on numerical analysis (for environmental noise and air pollution). The goal is to provide a quick idea on the impact of planning choices for non-experts that is applicable to the current region.

Note that there is a focus on noise abatements during propagation. Although source oriented measures like road surface optimization or vehicle speed reduction could be efficient, such choices are beyond the authority of the city who can only act on the surroundings of the ring road. In addition, the impact of source related measures on the final spatial design of the zone will be second order only; a well designed noise abatement solution is not limited to specific traffic conditions.

3.2.Step 2 : Co-create

The co-creation process has two levels of interaction: co-creation between the planning teams and field experts, including the urban sound experts, and co-creation with the local population. A schematic of these interactions is presented in Fig. 4. The first wave of co-creation mainly transferred knowledge from the field experts and the locals to the planning teams. An environmental noise expert gave a state-of-the-art presentation on road traffic noise and its abatement in a meeting with all planning teams together. The main concerns of the local population were identified during evening sessions organized by the planning teams, separately for each neighborhood.

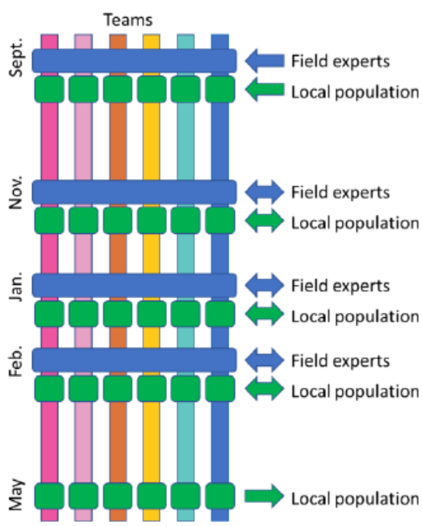

Figure 4. Timing of the interactions between the six planning teams and field experts and local population, during the intense co-creative planning process. The process is managed by the city department.

During the meetings, field experts had the opportunity to comment on and to help fine-tuning initial and more worked out designs proposed by the teams. The local population was continuously informed and consulted in the meantime. To enhance transparency, representatives of citizen groups could attend the meetings between the project teams and the environmental experts. This also ensures that citizens understand the full complexity of the planning process, to dispel myths on specific measures and to help realizing that budget constraints could direct choices in practice. Note that this (public) participative process also included other aspects than environmental sound. Specific co-creative procedures focusing on urban sound, however, do exist (see Xiao et al., 2017).

In between the co-creation sessions involving the teams and the urban sound experts, SWOT (strength, weakness, opportunity, treat) analyses were performed based on expert judgments. Environmental acousticians with a long track-record are needed for this. Without time-consuming and costly calculations, the environmental noise exposure can be initially strongly reduced.

In Figs. 5 and 6, a few examples are presented of such initial advise on first plans. A main remark is often that noise abatement solutions should be sufficiently continuous since interruptions could strongly deteriorate their efficiency. Somewhat related, connected building blocks may create quiet facades, having clear benefits for environmental noise perception (Öhrstrom et al., 2006). Building envelope greening (Van Renterghem et al., 2013) could further enhance such effects; green roofs prevent sound diffracting over the buildings and green walls could limit potentially annoying reverberation in between the parallel building facades (see Fig. 5). Another common remark is that when a main sound source is abated, secondary sound sources like a local busy road (see Fig. 6) or rail traffic (that might be initially masked) will start to dominate the sound environment. Corrective measures for these are then needed as well to have a significant noise exposure reduction in the end.

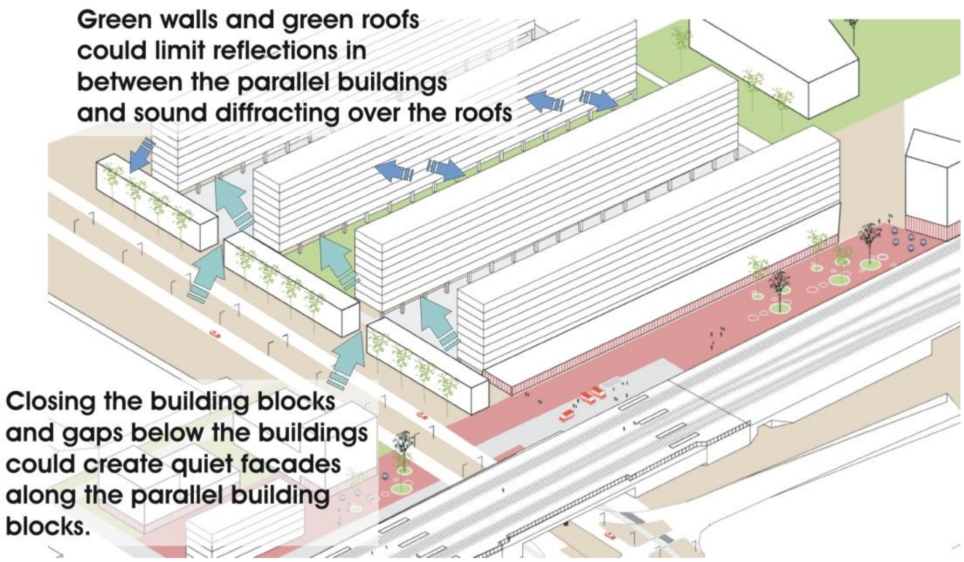

Figure 5. Example of initial advice by noise experts. A few changes are proposed to achieve quiet facades in the parallel building blocks (see Fig. 1, zone a).

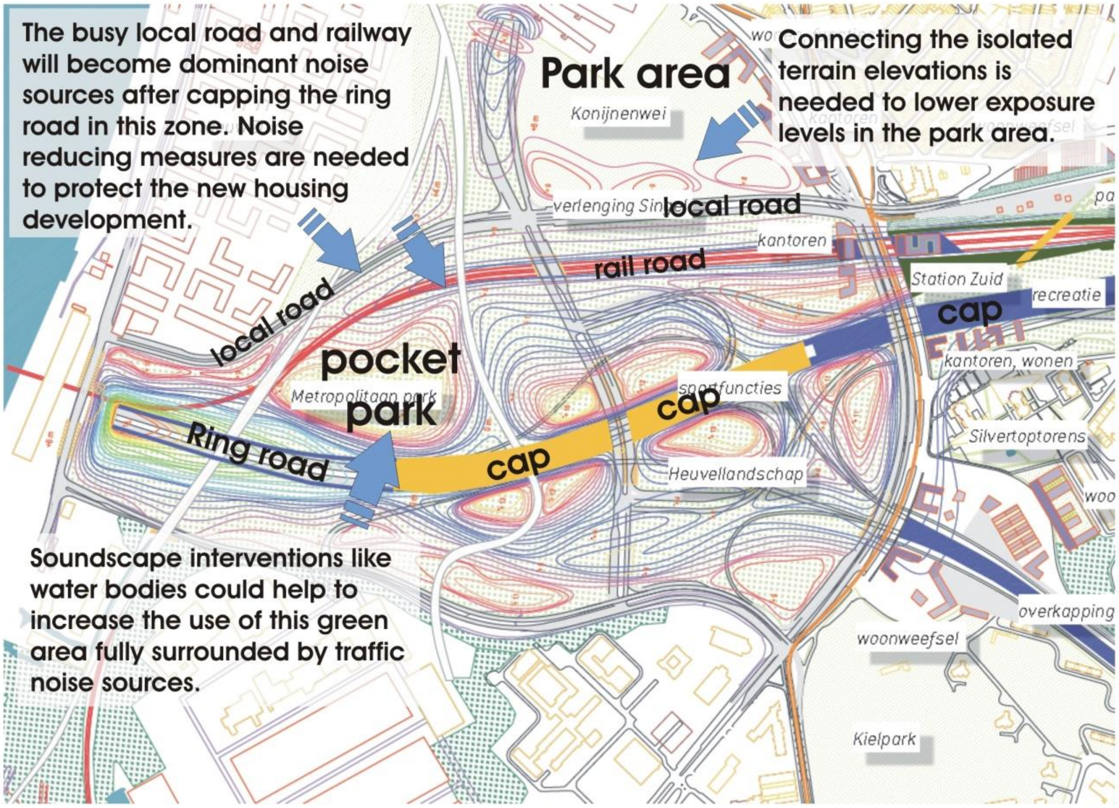

Figure 6. Example of initial advice by noise experts (see Fig. 1, zone b).

Similar (and sometimes combined) meetings were held with the other environmental topical experts, giving additional inputs and concerns to the planning team. In the next iteration, all expert remarks should then be combined to improve the plans. For teams that did not consider environmental noise exposure sufficiently, these meetings were used to raise awareness and indicate potential problems (and opportunities) in their zone.

While plans took shape, more specific questions were posed by the planning teams. Funding was available to consider these by detailed numerical simulations, allowing to study the feasibility of less common measures. Examples are the acoustical effect of a baffle-like partial coverage hanging over the road, or how the necessary holes/chimneys (for ventilation) on the caps radiate sound to the environment. Note that these are important inputs to further develop the plans. Such simulations (see Fig. 7) showed that these baffles, on condition that acoustic absorption is added to them, could be a useful noise abatement, potentially replacing other noise reducing measures that are more land taking and thus impacting the (visual) design of the zone under study. In the other example, a gradual grass-covered slope towards the chimney mouth was predicted (see Fig. 8) to hardly affect the radiation to the environment as a result of the noise produced inside the tunnel. The chimneys could thus be easily integrated in the intended park environment on the cap without affecting the noise exposure.

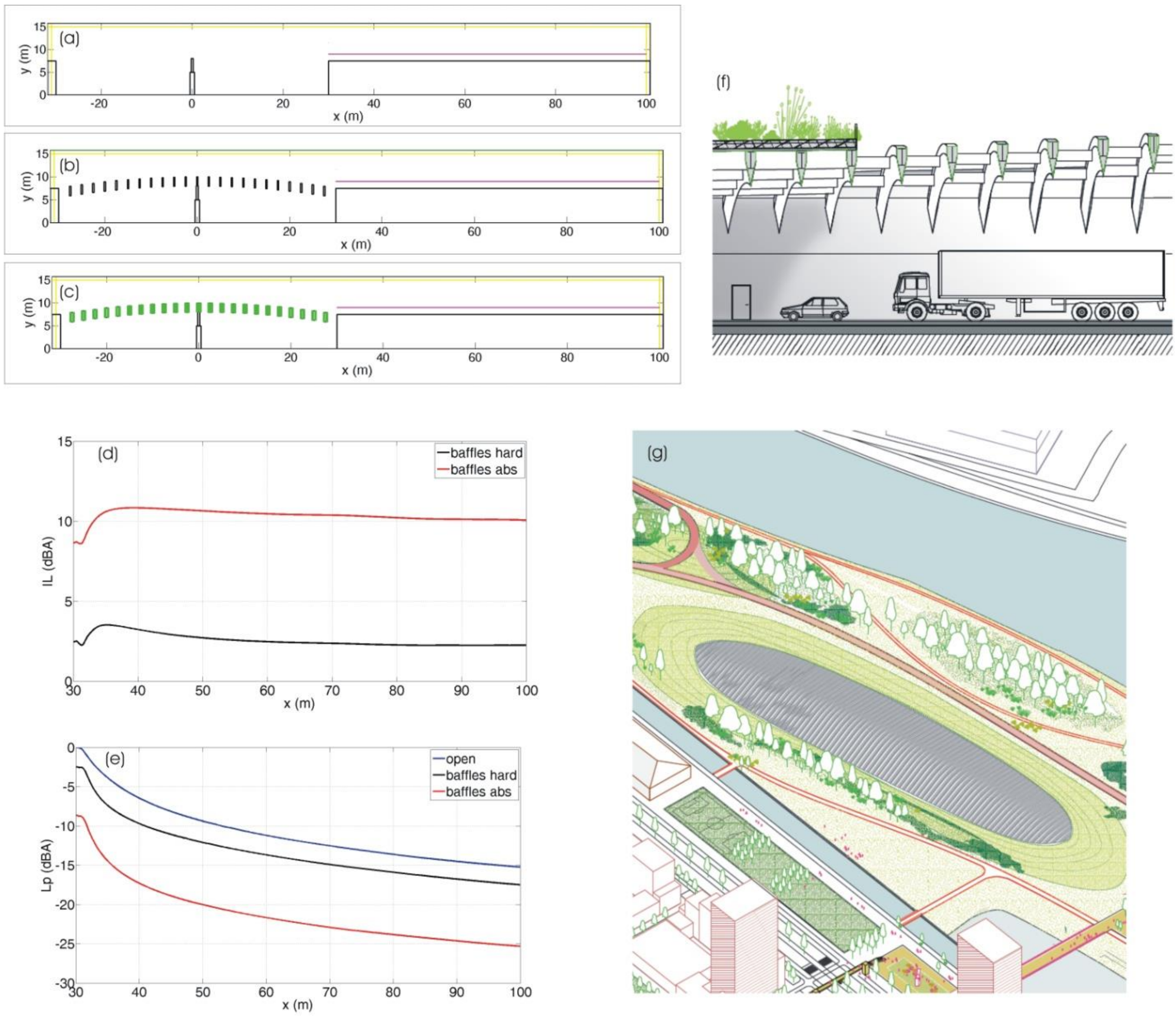

Figure 7. Example calculations related to a specific design question. Detailed simulations are used for the prediction of the effect of baffles (see (f) and (g)) hung over the road. In (a)-(c), the configurations are depicted, where (a) is the reference case (open, non-covered road), (b) uses rigid baffles and (c) absorbing baffles (using a non-ground based green wall substrate as discussed in Van Renterghem et al., 2013). In (d), the insertion loss relative to the open road (a) is shown in function of distance relative to the border of the depressed road at a fixed receiver height. In (e), the sound pressure levels relative to the level at the border of the road for the open case are shown (see Fig. 1, zone c).

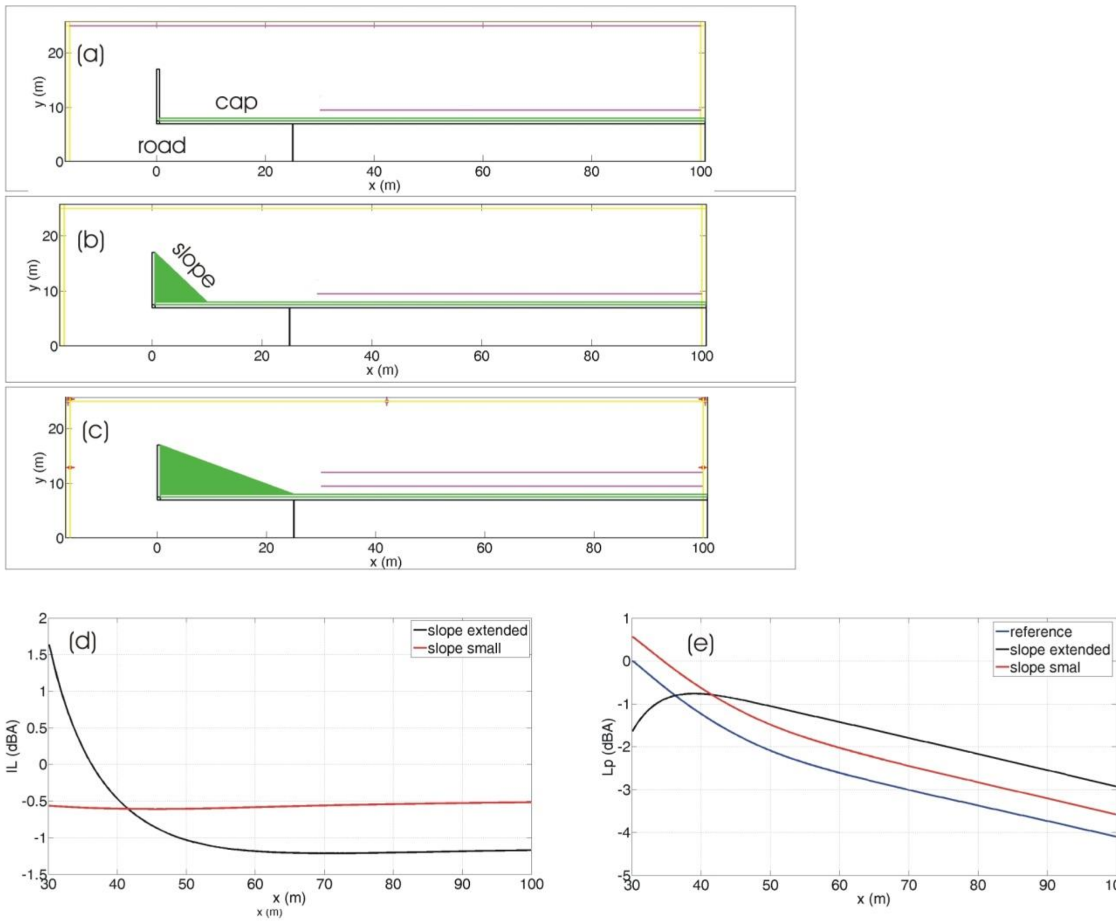

Figure 8. Example calculations related to a specific design question. Detailed simulations show the effect of embedding the chimneys in the newly created landscape on the cap (see Fig. 1, zone c). In (a)-(c), the configurations are depicted, where (a) is the reference case, (b) represents a steep and small grass covered slope towards the chimney mouth and in (c) a less steep slope is considered. In (d), the insertion loss relative to the reference case is shown in function of distance at a fixed receiver height. In (e), the sound pressure levels relative to the level at x=30 m in the reference case is shown.

Specific concerns raised by the population were considered as well. Road segments concentrating and surfacing after being tunneled (at the “Oosterweelknooppunt”, see Fig. 9) will radiate sound to the dwelling area across the river. As a result of the completion of the ring road, this could become a new noise source for the people living there. The simulations indicate that with a diffraction based measure (such as a thick gabion noise barrier; see e.g. Koussa et al., 2013), the predicted levels (see Fig. 9 (b)) are rather modest at the assessment point, and thus likely to be masked by other background noise. Also for the intended recreational space near the lake, at the same side of the river as the highway, these noise reducing measures are mandatory. Note that these are initial calculations and that further fine tuning will be needed when the full spatial details in this zone are known. But at least, this early consideration gives confidence that a viable solution is likely in the end.

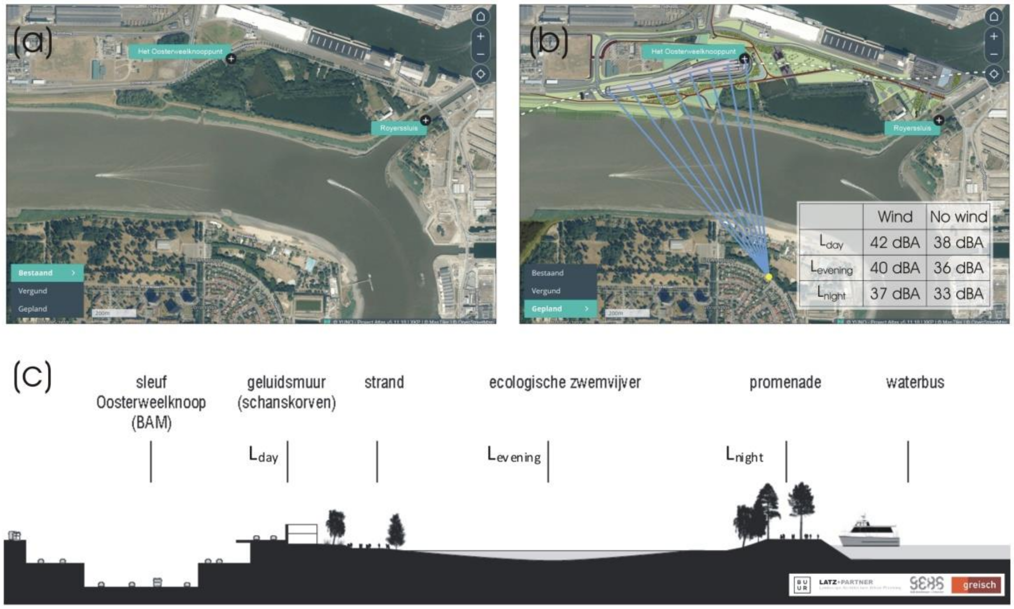

Figure 9. Example calculation of a specific raised issue; (a) current situation, (b) planned situation after closing the ring road, (c) proposed cross section near the source side including a noise reducing measure (gabion wall). In (b), the blue lines indicate a few sound paths between the surfacing road network and an assessment point central at the first line of dwellings across the river. The predicted equivalent sound pressure levels in (b) are for the day, evening and night period, following the END (2002). Sound propagation to the reference point is performed with the Parabolic equation method (Salomons, 2001). "Strong wind" corresponds to downwind sound propagation in case of wind speed exceeding only 5% of the year. Only the specific contribution from the traffic junction is considered here. (see Fig. 1, zone d).

3.3.Step 3 : Evaluate

In a final step, various planning scenarios should be compared regarding their environmental noise exposure. In urban sound planning, a diversification of the acoustical goals is necessary depending on the zone considered. Dwellings, public space including parks, and soft connections were identified in the current project.

3.3.1.Setting quantifiable criteria

3.3.1.1.Noise exposure at dwellings

Inside private dwellings, external noise should be as much as possible limited to prevent disturbing daily activities and communication, and to ensure adequate conditions for sleep. In early-stage sound planning, the outer facade exposure is then of main concern. Acoustical facade insulation, in contrast, should be considered when other measures fail or are insufficient. In many countries, good practice standards define the insulation needs based on outdoor facade levels. Limiting the outer building skin exposure could thus be cost efficient.

Note that people will also spend time around their dwellings, and when evaluating noise annoyance in surveys, neighborhood exposure is implicitly accounted for (Klaeboe, 2007). In addition, dwellers open windows. An open window leads to a strong loss in acoustic insulation along that facade (Jean, 2009; Locher et al., 2018). In addition, deliberately closing windows is not a preferred coping strategy for dwellers (Van Renterghem and Botteldooren, 2012).

When dealing with exposure at dwellings, measures improving noise perception could be considered as well. The benefits of a quiet side have been largely recognized and quantified (Öhrstrom et al., 2006; Gidlof-Gunnarsson and Öhrstrom, 2010; de Kluizenaar et al. 2011; Van Renterghem and Botteldooren, 2012). Further corrections could be made when accounting for audio-visual interactions in environmental noise perception. A strong effect is to be expected for visible vegetation as seen through the window both at the least and most exposed side (Van Renterghem, 2019). However, with current standardized engineering methods, only the front facade levels can be more or less adequately calculated and only this indicator is used here while evaluating the noise impact on dwellings.

Noise has various effects on people. Health effects could form a common ground for their quantification and might be especially useful for dissemination. At the same time, the link with other types of pollution could be made. The disability-adjusted number of life years lost (DALY) due to environmental noise exposure will be calculated. The latter is a commonly used concept in environmental impact assessment, expressing the cumulative number of years lost due to ill-health, disability or early death.

Not only the current population is considered, but also the people expected in new building developments where applicable. Knowledge on DALYs is available for noise annoyance, sleep disturbance and ischemic heart diseases, covering a major part of the noise-related health effects (Fritschi et al., 2011; WHO, 2018). Exposure effect relationships and severity weights taken from the WHO evaluation of burden of disease from environmental noise (Fritschi et al., 2011; WHO, 2018) were used. The L_{den} indicator, in line with the official noise maps to be reported to the European Commission following the END (2002), is used (at the most exposed facade) from which DALYs were estimated (Fritschi et al., 2011; WHO, 2018).

3.3.1.2. Noise exposure in the public space

The soundscape of the public space should match the envisaged use and should reflect its identity. The discrimination is to be made between wanted sounds and unwanted sounds. Unwanted sounds in the urban setting are typical of mechanical nature (as opposed to “human” or “natural” sounds), which is to a large extent traffic noise. Setting limits here makes sense, in contrast to when dealing with the wanted sounds.

An adequate indicator for characterizing tranquility is LA50 (De Coensel and Botteldooren, 2006), i.e. the A-weighted sound pressure level median. Based on a prior study of existing parks in the city of Antwerp (Filipan et al., 2017), LA50 below 50 dB showed to be a suitable criterion for the acoustic quality as perceived by park visitors. In extension, this condition can be used for any urban public place where a restorative function is envisaged. The A-weighted equivalent sound pressure level during daytime (L_{day}) will be used as a proxy for LA50, given the rather continuous nature of the ring road noise during daytime and the inability of noise mapping methods to accurately calculate statistical sound pressure levels.

In case of parks specifically designed to increase urban biodiversity, avifauna might be considered as a suitable indicator as these animals are sensitive to road traffic noise. Above an equivalent sound pressure level of 55 dBA, strong avoidance reactions have been experimentally observed (McClure et al., 2013) for a range of species. The previously set limit at 50 dBA L_{day} could serve both this goal and human restoration. Note that bird songs in the urban environment are among the most preferred human natural sounds (Viollon et al., 2002; Yang and Kang, 2005), and help to improve the general appreciation of the sonic environment and to mask road traffic noise in noise polluted urban parks (Van Renterghem et al., 2020).

While in dwellings the number of people is well known, this is not the case in the public space. Data on visitors of urban parks and squares is typically scarce, and predictions for newly created spaces might be even more challenging. As an alternative quantitative indicator, the surface area corresponding to the set limits was determined to allow comparing planning scenarios. Rather than the number of people exposed, this quantity shows the potential of a zone to fulfill its function from the viewpoint of noise exposure.

3.3.1.3.Noise exposure along soft connections

To promote cycling and walking, paths should have an agreeable soundscape. Clearly, many of such connections will run along roads and thus a too strict noise limit would make no sense. The criterion here is L_{day} below 65 dBA. This figure is based on long-term sound pressure level measurements performed along a cycling path bordering the ring road in its current form, with equivalent sound pressure levels during daytime more or less continuous at about 70 dBA (Van Renterghem and Botteldooren, 2018). A noise annoyance survey at this location (n=182) (Aletta et al., 2018) indicated that 45 % of the respondents categorized this zone as “calm” (as opposed to “busy”, in a forced choice question). Lowering the exposure level to 65 dBA is expected to ensure that more than half of the people would give the rating “calm”. The path length adhering to this limit is the indicator that will be used.

Note, however, that this part of the cycling path was strongly (visually) immersed in green by the presence of tall trees, whose positive effect on perception (Van Renterghem, 2019) might have played strongly. Similarly, a virtual reality perception experiment of walkers (n=71) on a bridge (Echevarria-Sanchez et al., 2017) crossing the Antwerp ring road showed the importance of green visuals. There, the pleasantness rating was found to increase with decreasing noise levels, but quite rapidly (roughly below 65 dBA; see Echevarria-Sanchez et al., 2017) the visual setting had a stronger effect. Both studies thus evidence that the landscape and visual quality along soft connections are important, and that a too strict emphasis on low levels is actually not needed.

3.3.2.Example : comparing various spatial designs regarding noise exposure

Based on the intense co-creation project with noise experts, it is expected that the main identified weaknesses in the designs were resolved, and opportunities to improve the environmental acoustics were at least considered. Not all advice from the acoustical experts was followed depending on the weight that was put on other environmental concerns or specific visual choices. Noise maps were calculated by the acoustical experts for a few planning scenarios.

The noise maps rely on traffic flow predictions, more precisely those expected once the Antwerp ring will be completed. Clearly, this involves many uncertainties and partly depends on political decisions to be made (such as toll in tunnels, speed limits, silent road surfaces, ...). In order to compare various planning scenarios in the zone directly bordering the ring road, this is probably not the main concern in the current planning phase. But clearly, zones where measures are most needed might be missed when traffic conditions change. Note that noise mapping involves many more choices (Licitra, 2013), but for the current illustrative purpose and comparison, a further description is deemed unnecessary since the same sets of parameters were used for each scenario.

In Fig. 10, L_{den} noise maps are shown for a specific zone. In variant A, terrain elevations (berms) were introduced along the highway infrastructure. In variant B, parts of the ring road were covered, and the newly acquired space was used for park zones. At some locations, noise walls were placed as well.

Variant C is a combination of berms (as in variant A) and capping parts of the highway (as in variant B). Table 1 presents the condensed outcomes as discussed in Section 3.3.1. Based on this analysis, variant B could be the preferred one, as this lead to the smallest number of DALYS for inhabitants in this zone, while the amount of restorative green space and agreeable soft connections is close to the optimal scenario C (when only considering these public space criteria). A detailed analysis and full description of this complex case is beyond the scope of this paper, but it at least shows an example of diversified decision making with relation to environmental noise exposure.

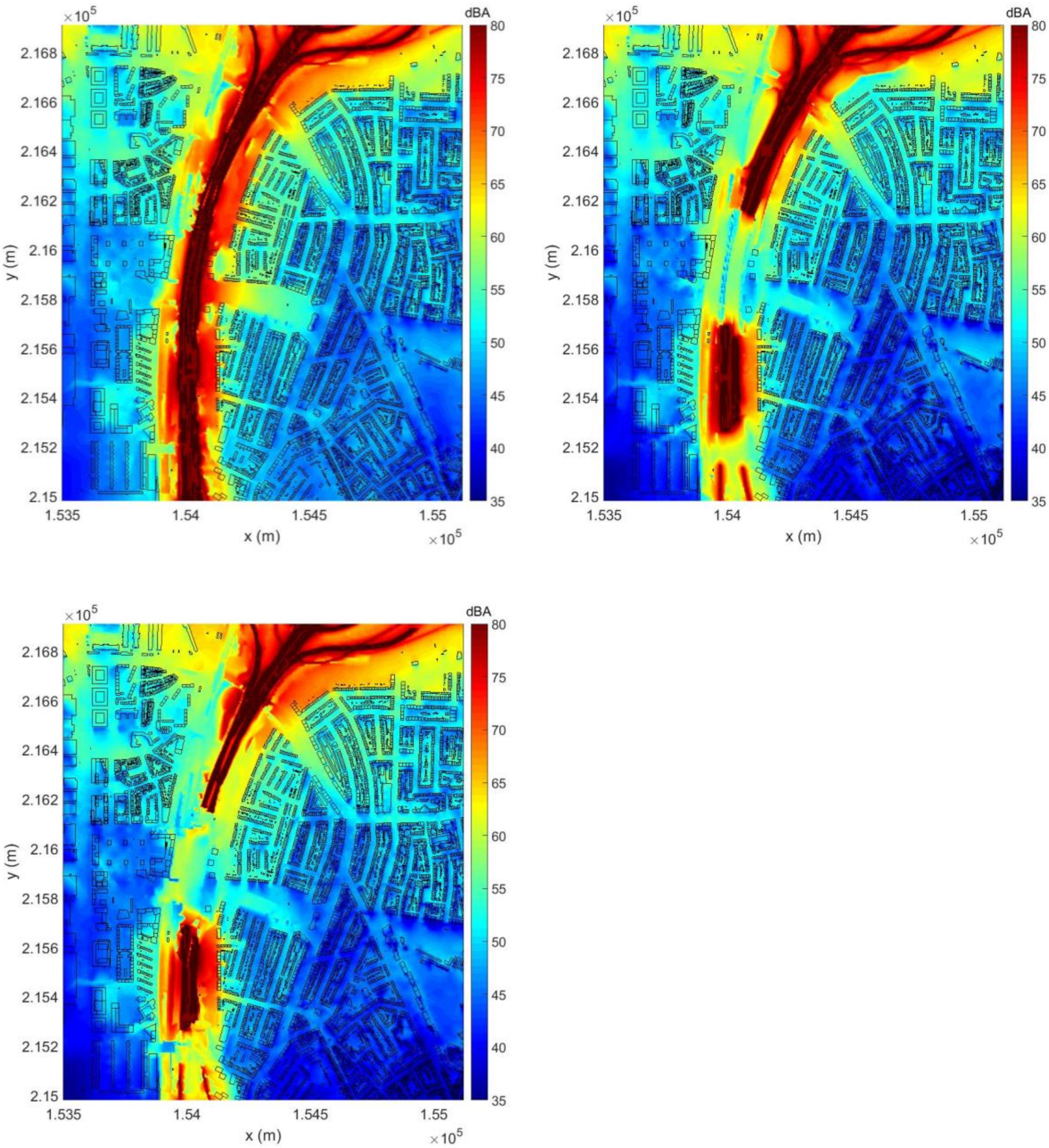

Fig. 10. Example noise maps of different planning scenarios for a specific zone near the ring road (see Fig. 1, zone e). The noise maps show L_{den} and were calculated with the CNOSSOS model (Kephalopoulos et al., 2012, as implemented in SoundPLAN, 2018).

Table 1. Example of a condensed evaluation, based on the noise maps presented in Fig. 10, using diversified acoustical goals.

	scenario A	scenario B	scenario C
Disability adjusted life years lost (DALYs, based on the most-exposed facade L_{den})	57.2	53.0	55.0
Surface of restorative urban green public space (in ha) (based on L_{day} < 50 dBA)	26.5	32.7	33.2
Length of agreeable soft connections (in km) (based on L_{day} < 65 dBA)	8.5	10.0	9.8

4.Discussion

Urban sound planning and design needs detailed spatial data. In an initial phase, architects and urban planners work with sketches and drawings. This information, however, should be directly concretized as geographic information system (GIS) data to allow quantitative evaluations with numerical tools. Data integrity and data aggregation (position of road networks and traffic parameters at each segment, terrain shape, location of dwelling developments, etc.) are identified as a main problem. Lack of completeness and imprecision, but also misinterpretations in the spatial design, could lead to erroneous noise maps. A large amount of manual labor is then needed to end up with correct input data. When high-rise buildings are present, detailed 3-dimensional information is needed as well for realistic exposure assessment. Note that the need for detailed spatial data when dealing with noise is much more pronounced than for other environmental aspects such as air quality.

Current noise mapping methods, even standardized and legally imposed ones, are inaccurate when more complex propagation aspects come into play. In the current project, where natural and landscape integrated solutions (Van Renterghem et al., 2015) are in focus, this is especially problematic. Noise mapping methods are nevertheless necessary to capture the full complexity of the presence of a multitude of sources in a zone. Less detailed sound propagation modules are then typically used for the sake of reducing computing times. The detailed simulation techniques for the study of specific and uncommon measures (see Section 3.2) are not applicable to a large area. However, care is needed to still include up-to-date measures in the final redevelopment plan, even though they cannot be directly visualized in the noise maps. Additional comments and qualitative/semi-quantitative data could then be helpful. As an example, the number of people where a quiet side benefit is expected could be reported based on building geometry analysis and expert judgment, without aiming at an exact prediction of front-back facade level differences.

At a more advanced planning stage, environmental sound auralization (see e.g. Pieren et al.) of specific scenarios might be considered. This is a powerful tool that could strengthen the quality of the co-creation and public participation process, especially since sound pressure levels or level reductions might be rather abstract for non-specialists. To go even further, virtual reality (VR) renderings ensure that audio-visual interactions become evaluated as well. In the current project, various planning scenarios of a bridge crossing the highway under study were evaluated in VR (see Echevarria-Sanchez et al., 2017), leading to useful insights (Section 3.3.1.3).

Concerning the evaluation process itself, a few observations can be made. DALYs put the effects of re-development in a broader perspective, but this indicator might be less sensitive to changes and thus less convincing for the public at large. Quantification of soundscape and perception measures on environmental noise related DALYs does not seem sufficiently mature when analysing the current state-of-the-art. A possible approach to still use level-based dose-effect relationships is assuming an equivalent level reduction having a specific health-related outcome in mind. A quiet building facade (Öhrstrom et al., 2006) and vegetation as seen from the dwelling (Van Renterghem, 2019) have both been roughly quantified (at 5 dBA and 10 dBA, respectively) in terms of noise annoyance reduction. Note that this is only one of the health-related effects of environmental noise exposure.

Other evaluation indicators proposed in this work, like the length of agreeable soft connections and the surface of public space where a suitable soundscape could be created, still rely on levels. But they do account – at least to some extent – for a few environmental sound perception and soundscape ideas as discussed in Section 3.3.1.2 and 3.3.1.3. These indicators seem more sensitive than DALYs for comparing planning scenarios. Note that other approaches for decision making or priorization of noise action plans can be found elsewhere (Licitra et al., 2017).

In the current methodology, only the impact of the environmental noise issue on the planning process was considered. The interaction with air pollution, the other major environmental human health concern in the zone under study, is beyond the scope of the current work. Especially when green measures are promoted for both noise reduction and air quality improvement, some care is needed as some measures might be contradictory (see e.g. Vos et al., 2013; Van Renterghem et al., 2015). In a final evaluation phase, combined noise-air quality indicators (see e.g. Silva and Mendes, 2012) might be helpful. Since DALYs are commonly used to assess the health impact of air pollution on the population as well, this approach could be interesting for a more holistic impact assessment of spatial planning scenarios.

5.Conclusions

In this work, a sound planning methodology was crystallized (see Fig. 11) from the experience gathered with a large urban redevelopment project focusing on road traffic noise. Internalization of sound in the planning process was shown to be possible but not straightforward. Based on the experience gathered with the Antwerp ring road project, following guidelines can be formulated:

1. Including an initial phase in the process, where stakeholders are informed and educated regarding the latest state-of-the-art in environmental noise abatement, is very useful. It sets the minds to an environmental aspect that is tightly interwoven with urban spatial planning but often neglected.
2. Considering dwellings, public space, and soft connections as different domains is necessary because of the different approaches that are needed while designing and evaluating.
3. In large multi-stage development projects, each planning phase should be assessed and optimized to allow maximum freedom in the next stages and to avoid jeopardizing opportunities in creating pleasant and healthy living environments. A close interaction with noise experts is thus needed throughout the whole process.

Although the current paper provides a useful framework, further refinements might be needed when experience is gained from other early-stage sound planning case studies. In addition, continued work is needed to translate, in a quantitative way, knowledge from soundscape and environmental noise perception studies to the urban sound planning process.

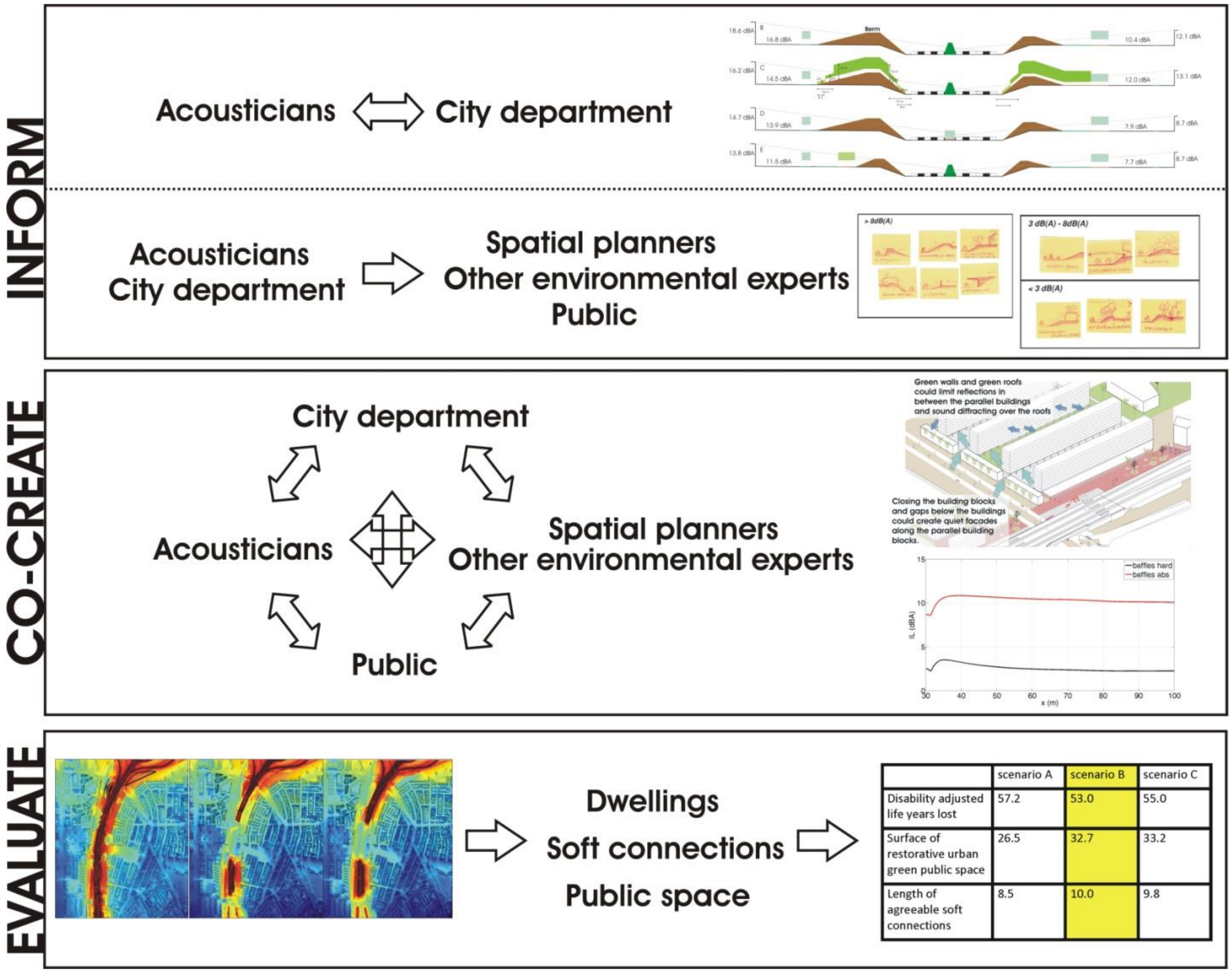

Fig. 11. Summary of the proposed planning methodology to come to a realistic redevelopment scenario regarding the environmental noise exposure. Example output from the current case study is added at each stage.

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Competing interests statement

No competing interests to declare

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